SELECTION OF TITANIUM ELECTRON-BEAM WELDING TECHNOLOGY

Electron-beam welding of titanium in magnetic lens with lithium cooling

It's necessary to weld two identical joints in magnetic lens [1]. The joints are round; the centers of circles are situated on the lens axis of symmetry. Welds are located on the opposite ends of the lens – these are the ends of tubes put one into another. The thickness of tubes walls is 1.5 mm; the joint diameter is 23 mm.

1. Welding of titanium plates of 1.5 mm thickness

Electron-beam welding of the plates with four variants of edges grooving should reveal the most appropriate variant of grooving and welding mode, i.e. beam current, welding rate and beam focusing influence.

03.12.98 *Plates positioning into vacuum chamber of electron-beam welding facility*

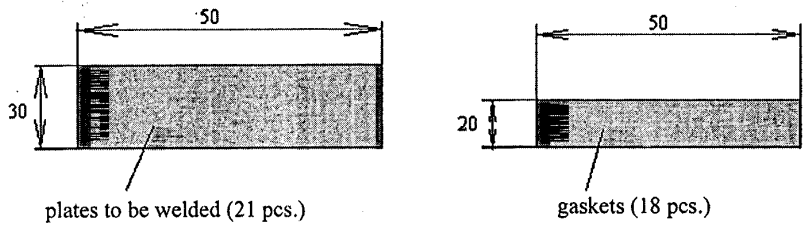

Fig. 1 Form of titanium plates

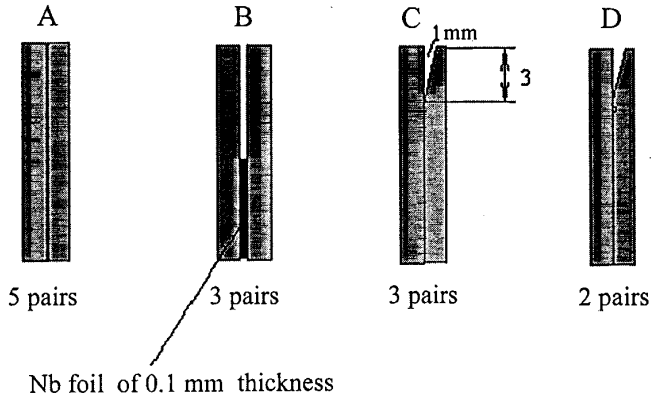

Fig. 2 Edge grooving of titanium plates

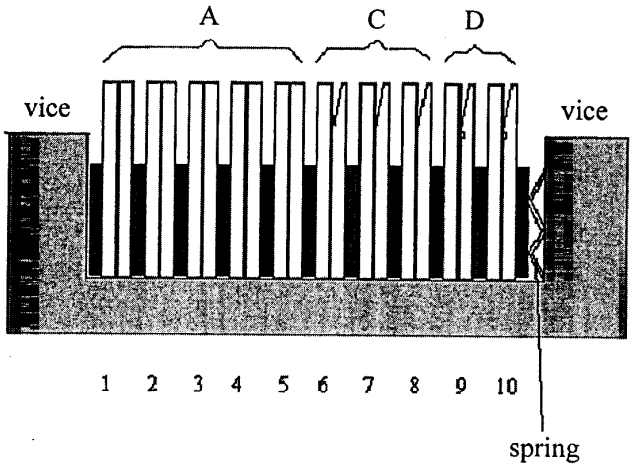

Fig.3 Plates laying for welding.

04.12.98 Electron-beam welding of the plates

Comment:
1) Plates of B-variant edges grooving were welded separately.
2) There was made a groove 0.5×0.5 mm in variant D to limit the melting zone along the straight line.

Selection of the focusing current: electron beam is directed in vertical top-down direction. At a low current the beam is focused with focusing current of I_f = 726 mA. The beam focusing lower than the plates ends by 30 mm occurs at a current I_f = 711 mA

Comments:
1) Focusing current is the current in magnetic focusing lens of the facility;
2) During welding when the beam current is increased the plane of beam focusing is higher than that during the adjustment with low electron-beam current (0.5 mA). The focal length dependence on beam current is nonlinear.

Welding regimes for the joints #1÷10 shown in Fig. 3 are given in Table 1

Table 1

Joint number /welding regime	1	2	3	4	5	6	7	8	9	10
Current of welding, mA	3; 15	5; 15	15	20	20	10	10	15	10	20
Welding rate, mm/s	5	10	10	10	20	10	10	10	8	10
Focusing current, mA	726	726	711	711	711	711	719	719	719	719
Result: b-bad, f-fair.	b	b	b	b	b	f	f	b	f	b

Comment:
1) Welding regimes of plates with edges grooving (variant B) are the same as for joints #1, 2, 3. The result is – b, b, b.
2) The appearance of bad weld – it is rough, hilly and with drops of melted metal.
3) Samples 1 and 2 were welded twice. Melted metal drops were not observed during the first welding (at beam current 3÷5 mA)

Summary 1:

1) Variants C and D of ends grooving for titanium welding are the most preferable. The result of welding doesn't depend on focusing current (in I_f = 711÷726 mA limits) practically. So it is possible to use such focusing current which was selected during the adjustment at low beam current.
2) Regimes of welding: beam current ≤ 10 mA; welding rate ≤ 10 mm/s.

2. Welding of round titanium joints in presence of ceramics

Comment:

1) Welded tubes in magnetic lens are separated by ceramic layer, beginning in a distance of 5 mm from the edge and lasting farther between tubes. Some gas emission affecting the joint quality can occur during welding. The goal of this samples welding is revealing the influence of ceramics on the joint quality.
2) The size of the lens doesn't allow placing it in welding facility so that to get top-down direction of electron beam during welding. The beam slope angle with vertical line is ~75° and welding of samples was made with such slope of electron beam.
3) The welding rate of round joints 23 mm in diameter is <5 mm/s – it is a hardware limitation. The samples were welded with 4.6 mm/s welding rate.

07.12.98. *Welding of sample with inserted ceramic ring.*

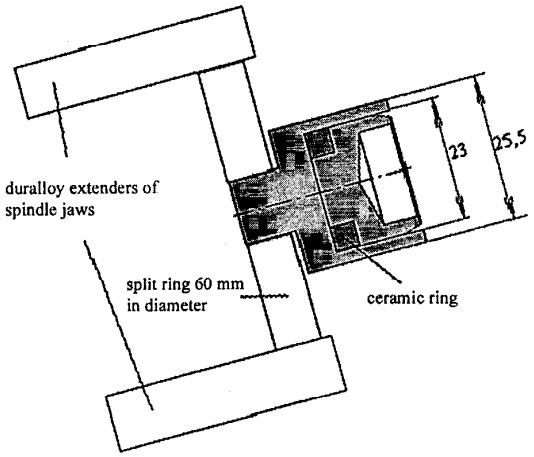

Fig. 4 Geometry of welding of sample with inserted ceramic ring.

Table 2

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	92
The duration of welding beginning and end, s	0.5; 2.0 \ 0.5;2.0

Comment:

1) The joint was welded twice. The welding currents mentioned in Table 2 are separated by ";"
2) The duration of welding beginning and end: the durations of nonlinear process of current increase and drop at the beginning and end of welding procedure are given. The first number characterizes the duration of rise/drop in case if this rate would not change and would be equal to the initial rate value. The second number is the total duration of the whole process of current rise/drop with decreasing speed. When this numbers are equal the current rise/drop rate does not change.

The result of welding: the joint is fair, the end of weld is noticeable i.e. there is lowering of edge by 0.5 mm in 5 mm region. It is necessary to decrease the joint length by 5÷7 mm (reduce the overlap) or change the current rise/drop time.

15.12.08. *Welding the components with ceramics coated surface of inner tube (the components look like a half of real lens part).*

Comment: ceramic coating is made by the same technology as used in lens manufacture.

Table 3

Welding regime	
Welding current, mA	2; 3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	D
Joint length (πD = 72.3 mm), mm	85
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Comment: the joint was welded three times. The welding currents values in Table3 are separated by ";".

The result of welding: the joint is good, only the end of welding can be observed as a small pit of 0.5 mm depth in 5 mm region.

Summary 2: The quality of joint is not affected by the presence of ceramics.

3 The joints welding of magnetic lens. The investigation of the initial and final parts of welding joint.

16.12.98 *Welding of the first joint of magnetic lens.*

Table 4

Welding regime	
Welding current, mA	2;3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	D
Joint length (πD = 72.3 mm), mm	85
The duration of welding beginning and end, s	2.0;2.0 \ 2.0;2.0

Comment:

1) The joint was welded three times. The corresponding welding currents are separated by ";" in Table 4

The result of welding: the joint is fair; one can see the end of welding – a small pit of 0.5 mm depth in 5 mm region

Measurements of the real duration of current rise/drop time at the beginning/end of welding.

Comment:
The beam trace on the copper foil with 1 mm thickness was investigated. The foil ring is fastened around the lens so that its center coincides with the lens axis. The trace of beam on the foil and dimensions of joint beginning/end are shown in Fig. 5. The regimes of this welding are given in Table 5.

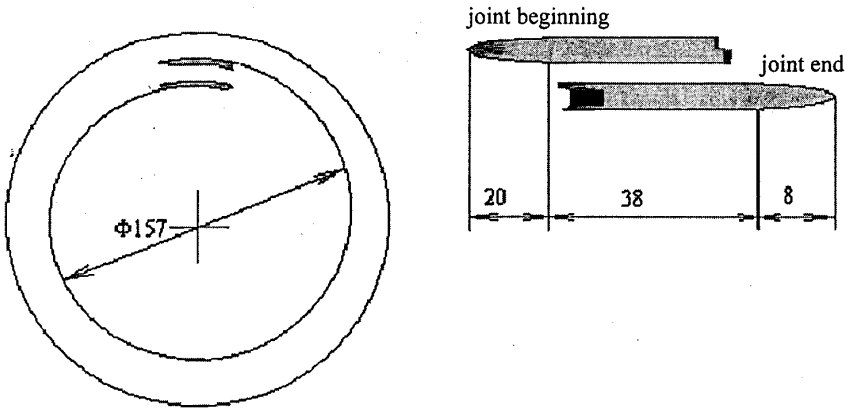

Fig. 5 Geometry of measurements of the real duration of current rise/drop time at the beginning/end of welding.

Table 5

Welding regime	
Welding current, mA	7
Welding rate, mm/s	31.4
Joint length (πD = 493 mm), mm	581
The duration of welding beginning and end, s	2.0;2.0 \ 2.0;2.0

Result:
The joint (157 mm in diameter) length can be reduced by 38 mm (one can see the beam trace also from the reverse side of the foil – it is the result of through fusion, but its shorter there – 25 mm.) The joint of 23 mm in diameter can be shorted by 5.6 mm.

17.12.98 *Welding of magnetic lens second joint*

Table 6

Welding regime	
Welding current, mA	2; 3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	D
Joint length (πD = 72.3 mm), mm	80.5
The duration of welding beginning and end, s	2.0;2.0 \ 2.0;2.0

Comment: the regimes of welding are the same, only the joint length is shorter by 4.5 mm.
Result: The small pit at the end of the joint remains.

3 Preparation for welding of the second lens. Welding completion parameters. The annealing after electron-beam welding.

Comment:
1) The welding completion parameters are: the length of welding joint, the duration of beginning/end of welding.
2) The assumption about the necessity of annealing of titanium details after welding was checked.

22.03.99 *Welding of samples (titanium tubes).*

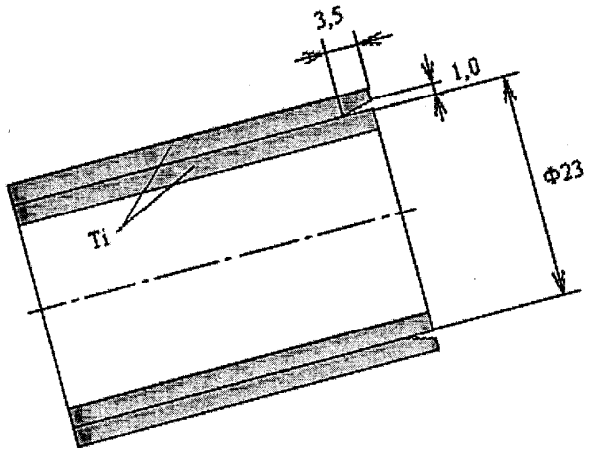

Fig. 6 Welding of samples (titanium tubes) geometry.

Table .7

Welding regime	
Welding current, mA	2; 3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	D
Joint length (πD = 72.3 mm), mm	76.0
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Comments:
1) The regimes of welding are the same, only the length of joint is shorter by 4.5 mm. The parameters of beginning/end of welding are different.
2) The annealing of side surface of the tube by defocused beam I_f = 643 mA (the sharp focusing occurs at I_f = 724 mA). The spot is 10 mm in diameter, red heated, 3 slow turns of the detail within ~5 minutes.

Result: the small pit at the end of the joint remains.

30.03.99 *Welding of the second tube (the same one) without annealing after that.*

Table 8

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	D
Joint length ($\pi D = 72.3$ mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Comment: welding regimes are the same, only the joint length is shorter by 2.5 mm.

Result: the joint end looks much better.

03.04.99 *Opening the joints. Tensile test.*

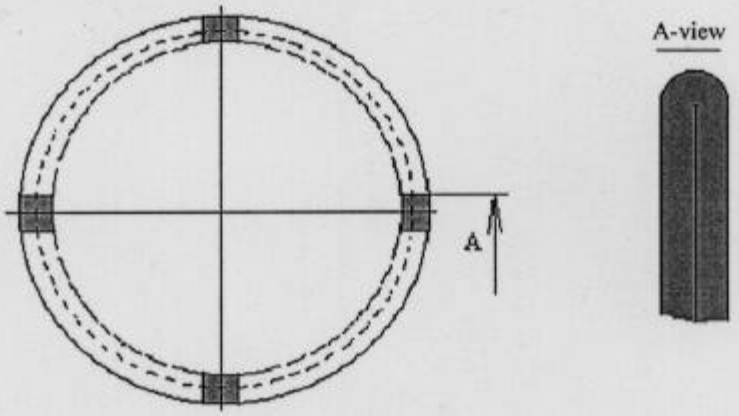

Рис.7 Geometry for tensile test

Comment: There are deep milled cross-cuts in welding joints as it's shown in Fig. 7

Result:

1) The welding joint is straight and has the equal-depth fusion (see A-view). The fusion zone reaches exactly the bottom (edge) of junction conical cut for welding and does not spreads farther. There is no necessity to make the restrictive groove in D-variant, because the fusion does not reach it. The C-variant is enough.
2) The tensile tests have shown that the joints on the both tubes are of the same fragility. It is necessary to test the effect of annealing in the oven after welding.

Summary 3:

1) The annealing after welding is necessary.
2) The electron-beam annealing has no effect.
3) "C" is the most preferable variant of edges grooving.
4) The most preferable parameters of welding beginning/end are:

Joint length($\pi D = 72.3$ mm), mm	73.5 (overlap 1.2 mm)
Duration of welding beginning\end, s	0.5;2.0 \ 0.5;2.0

4 The investigation of influence of annealing in the oven after electron-beam welding.

Comment:
Welding of three same specimens (see Fig. 8) made of titanium VT1, VT5, VT6-marks with the following annealing in the oven and welding the sample with shape similar to half a lens with soldered copper contacts was undertaken for testing the influence of annealing on the brazing.

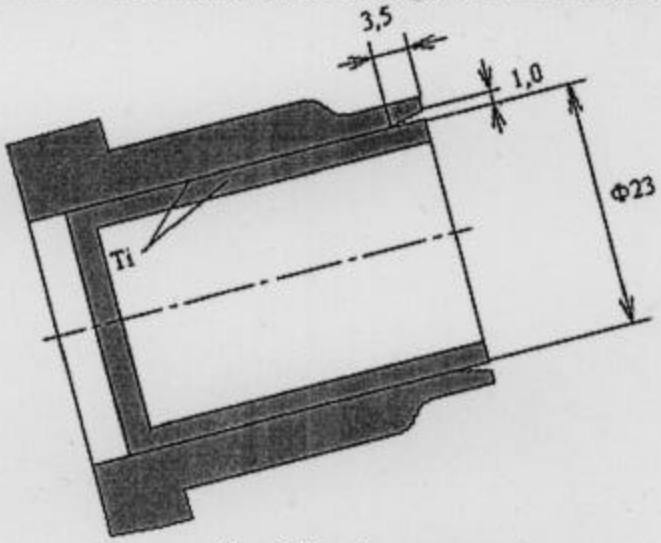

Fig. 8 Specimen geometry

08.04.99 *Welding of the first sample made of titanium VT1.*

Table 9

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Comment: the detail rotation (welding direction) is such that melted metal remains under electron beam.

Result: The end part of weld is easily visible – it has clear border but without pit. It's necessary to defocus electron beam on the final part of joint then it will be less noticeable.

09.04.99 *Welding of the second sample made of titanium VT5.*

Table 10

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Comment: The detail turning is in opposite with mentioned above direction i.e. melted metal remains above the beam.

Result: The joint looks the same as in previous case, so the welding direction does not affect the result.

09.04.99 *Welding of the third sample made of VT6 titanium.*

Table 11

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

09.04.99 *Welding of the fourth sample made of VT5 titanium*

Table 12

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Annealing results: The joints of all samples were strong enough after annealing.

Summary 4:
It is necessary to anneal titanium details in the oven after electron-beam welding.

5 Welding of magnetic lens

23.04.99 *Welding the lens first joint.*

Table 13

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length (πD = 72.3 mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

24.04.99 *Welding of the second lens joint.*

Table 14

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length ($\pi D = 72.3$ mm)	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0

Result: The welding procedure was successful.

6 Conclusion

1) "C" is the most preferable variant of edges grooving for titanium welding.
2) It is possible to use such focusing current which is defined during adjustment at low beam current.
3) The joint quality is not affected by the presence of ceramics
4) The annealing in the oven after welding is necessary.
5) The electron-beam annealing has no effect.
6) Welding regimes of round joint 23 mm in diameter are in Table 15:

Table 15

Welding regime	
Welding current, mA	3; 8
Welding rate, mm/s	4.6
Variant of edges grooving	C
Joint length ($\pi D = 72.3$ mm), mm	73.5
The duration of welding beginning and end, s	0.5;2.0 \ 0.5;2.0